

IMPORTANCE OF HELIUM-3 FOR THE FUTURE

Gerald L. Kulcinski

I. Historical Perspective

Scientists first proposed the use of thermonuclear energy for civilian applications in the 1950's. This work closely followed on the heels of the Hydrogen Bomb, and it was felt that commercial fusion energy would take only a few decades to perfect. Unfortunately, the difficulty of controlling plasmas (collections of charged particles and electrons) at temperatures 10 times hotter than the center of the sun proved to be much more difficult than originally anticipated. Most of the 1960's was spent developing the field of plasma physics and laying the ground work for a theoretical understanding of plasmas. By the end of the 1960's, and with unprecedented cooperation between U.S. and Soviet scientists, it became apparent that once the plasma physics problems were solved, significant technological progress was also needed to develop a safe and clean power source. Thus, in the 1970's, a dual approach to the problem was pursued: 1) several large plasma physics facilities were constructed to test the theories developed in the 1960's and 2) engineering analyses of power plant designs were initiated to ascertain the technological, economic, safety, and social implications of this new form of energy. Both of these lines of research have been continued in the 1980's with a major milestone of energy breakeven (i.e., the point at which as much energy is emitted from the plasma as it takes to keep it hot) within our grasp as we move into the 1990's. The current plan is to construct several large reactor-like facilities in the 1990's which will produce power in the 500 to 1000-megawatt regime and to use these facilities to test materials and power conversion schemes that might be used in the 21st century.

The worldwide fusion effort is now roughly equal in Europe, Japan, the United States and the USSR. In the early 1980's, approximately 2 B\$ per year was being spent on fusion research with the U.S. in the lead of that effort. Today, the total effort is slightly less, but it is clear that the European program has taken the lead from the U.S. and that a strong challenge for 2nd is being made by the Japanese. Altogether over 20 B\$ in then current dollars has been spent worldwide on fusion research since the early 1950's.

Further descriptions of the fusion process can be found in the references [1, 2], and only those aspects of this fuel cycle important for this paper will be repeated here. The reader is strongly urged to consult the references for more information on fusion.

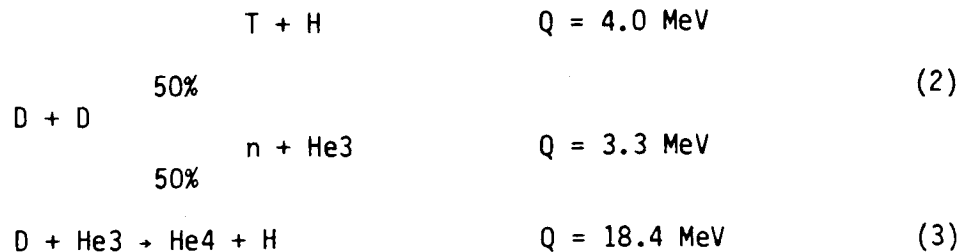
II. Relevant Plasma Physics Principles of Thermonuclear Research

Since the early days of the civilian thermonuclear fusion program, scientists had always envisioned that fusing a deuterium (D) and tritium (T) atom at very high temperatures (see equation 1) would prove to be the most favorable for the production of electricity.



Energy released,  $Q = 17.6$  Million Electron Volts (MeV)

There were several reasons why this choice was made, ranging from the fact that the DT cycle ignites at the lowest energy (see Figure 1) to the experience gained from the thermonuclear weapon program in breeding and handling tritium. Two other reactions, listed below, were also briefly considered.



Neither of these reactions has received much attention since the 1950's, because they both require higher temperature (see Figure 1) to ignite and because, there was no significant resource of He3 available on Earth.

Several things have changed since those early days of fusion research, and two of these will be addressed in this chapter. First we will address the changing situation in fusion physics, and second we will address the renewed interest in the technological and environmental advantages of the D-He3 cycle. The question of the He3 fuel supply will be addressed at the close of this chapter.

### III. State of Plasma Physics as it Pertains to the D-He3 Cycle

Simply stated, the objective in magnetic fusion research is to heat the confined plasma fuel to sufficiently high temperatures (T) at high enough densities (n) and for long enough times ( $\tau$ ) to cause substantial fusion of atoms to take place. Mathematically stated for a reactor using the DT cycle, this can be given as;

$$n\tau \geq 2 \times 10^{14} \text{ seconds per cm}^3 \quad @ T \geq 20 \text{ keV (200 million } ^\circ\text{C)} \quad (4)$$

Some perspective on the rate of progress in producing these conditions is given in Figure 2A where the  $n\tau T$  values achieved are plotted with respect to when they were first attained and 2B which shows the progress toward energy breakeven. The  $n\tau T$  product has been increasing at the phenomenal rate of a factor of 100 every 10 years. In fact in one parameter, namely the temperature T, scientists have actually produced 30 keV ions in TFTR plasmas at the Princeton Plasma Physics Laboratory (PPPL). This is 50% higher than needed for a DT reactor and only a factor of 2 lower than needed for a D-He3 reactor. The appropriate  $n, \tau$ , and T values required for a D-He3 reactor are

$$\begin{array}{rcl}
 n\tau \geq 4 \times 10^{15} \text{ seconds per cm}^3 & & (5) \\
 \text{at } T \approx 60 \text{ keV (600 million } ^\circ\text{C)}
 \end{array}$$

A detailed physics analysis shows that the Compact Ignition Torus (CIT) at PPPL could achieve the temperatures above in the mid to late 1990's.

# MAJOR FUSION FUEL REACTIVITIES

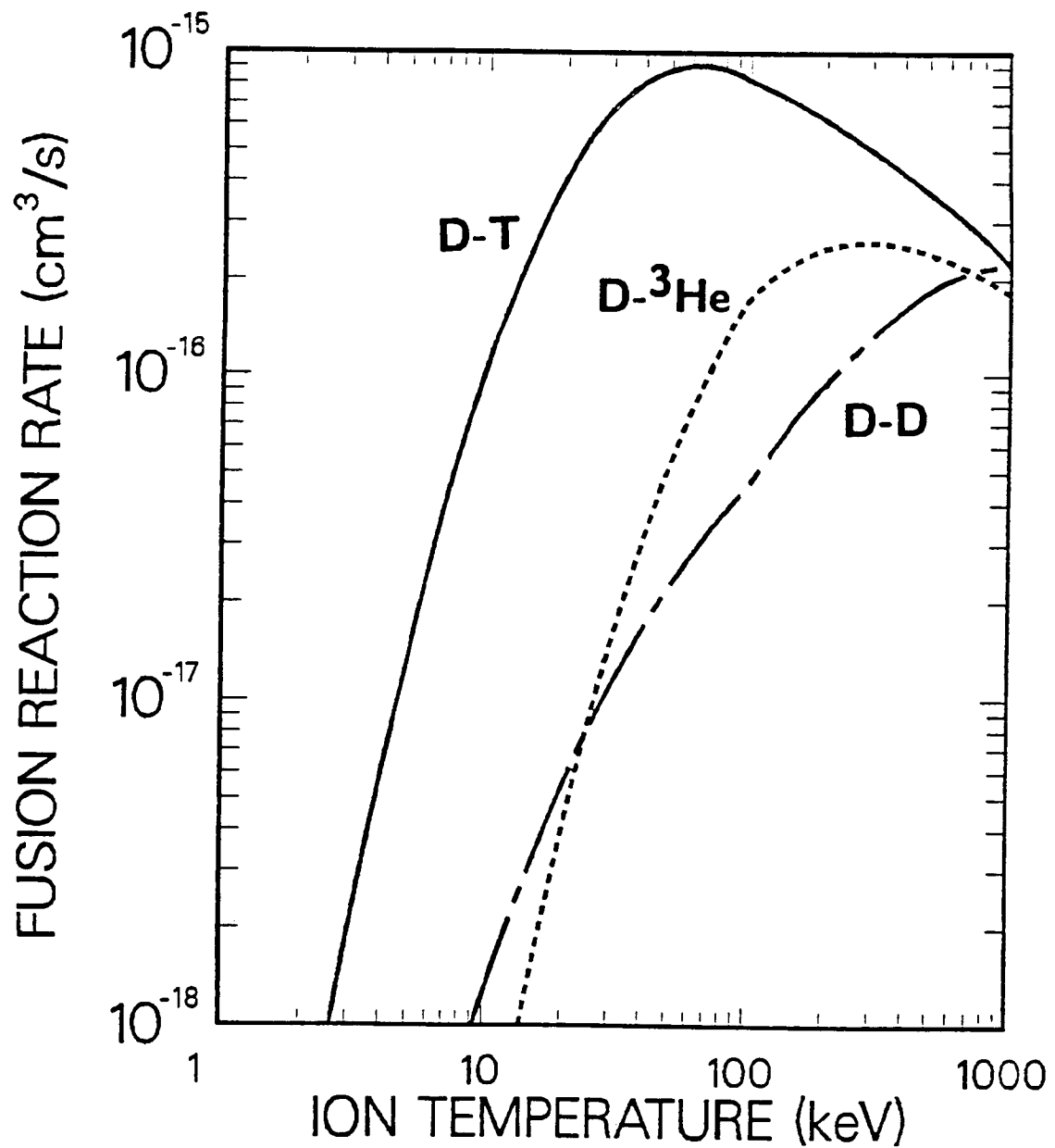


Figure 1. Major Fusion Fuel Reactivities

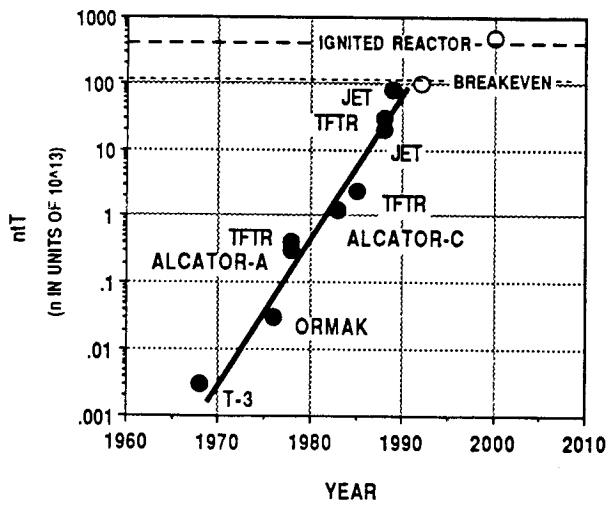


Figure 2A. Steady progress in the 3 major physics parameters for DT fusion.

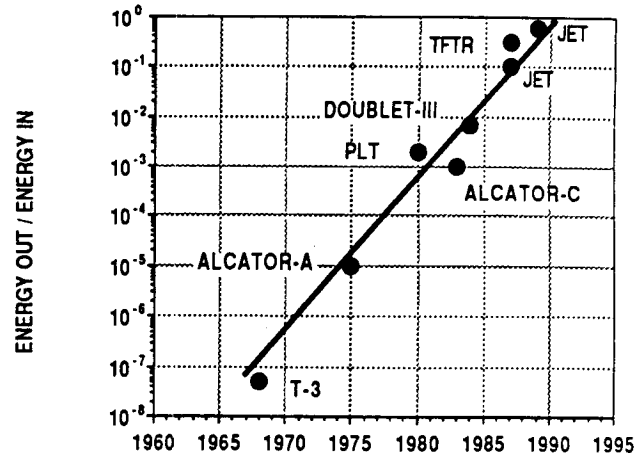


Figure 2B. The progress toward energy breakeven conditions has shown an increase of over 1000 every 10 years for the past 20 years.

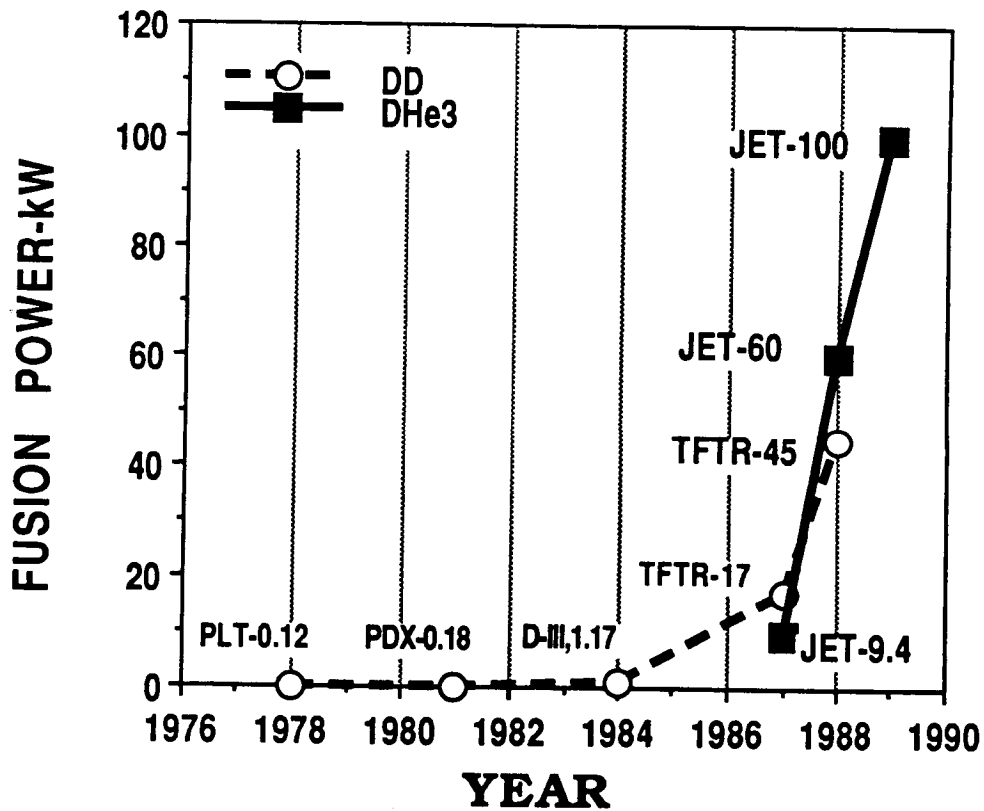


Figure 3. Actual release of thermonuclear energy in the laboratory by the DD and D-He3 reactions from the PLT, PDX and TFTR devices at Princeton, the D-III device at General Atomic, and the JET device in Culham, England.

While it is necessary to reach a  $n_T$  product of  $\sim 100$  (in units of  $10^{13}$ ) for breakeven in DT and a value of 400 for DT reactor operations (Figure 2A), it is necessary to achieve a  $n_T$  product of 24,000 for the D-He3 reactor. Recent analyses show that such values could be achieved by small modifications of the Next European Torus (NET) or the International Thermonuclear Experimental Reactor (ITER) currently being designed for operations around the year 2000. In other words, despite the factor of 60 required in  $n_T$  values for a working D-He3 power plant over a DT system, several possibilities to achieve those values are known.

The surprising historical point of the previous discussion is that only a few short years ago, most scientists would have believed it impossible to produce the necessary D-He3 reaction conditions before the year 2020 or even later. However, scientists at JET have recently produced 100 kW of thermonuclear power with the D-He3 cycle (see Figure 3). The possibility that significant power could be produced with He3 before the year 2000 has opened up a whole new class of studies within the past 2 years and caused a complete reassessment of our long-range goals in fusion research.

#### IV. Technological Benefits of the D-He3 Fuel Cycle

One of the key features of the D-He3 reaction in Equation 2 is that both the fuel and the reaction products (protons and He4) are not radioactive. However, some of the deuterium ions do react with each other producing a small amount of neutrons and tritium. When the cross section and fuel mixtures are included, one can calculate how much of the average energy release is in the form of neutrons (see Figure 4). Whereas the DT cycle releases 80% of its energy in neutrons regardless of the plasma temperature (and the DD cycle releases  $\sim 50\%$  in neutrons) one can see that operation at  $\sim 60$  keV with a 3:1 ratio of He3/D, can result in release of as little as 1% of the energy in neutrons in a D-He3 plasma.

Why is this important? The radioactivity and radiation damage of reactor components is directly proportional to the number of neutrons produced. Since the energy released per reaction from DT and D-He3 is roughly the same, the problem associated with neutrons can therefore be reduced by almost 2 orders of magnitude (i.e., a factor of 80).

The main technological advantages resulting from these characteristics of the D-He3 fuel cycle, when compared to the DT cycle, are summarized as follows:

- a) Increased electrical conversion efficiency.
- b) Reduced radiation damage.
- c) Reduced radioactive waste.
- d) Increased level of safety in the event of an accident.
- e) Lower cost of electricity.
- f) Shorter time to commercialization.

Only a very brief comment on each of these features will be made here and the reader is referred to several recent publications by the authors for a more in-depth analysis.

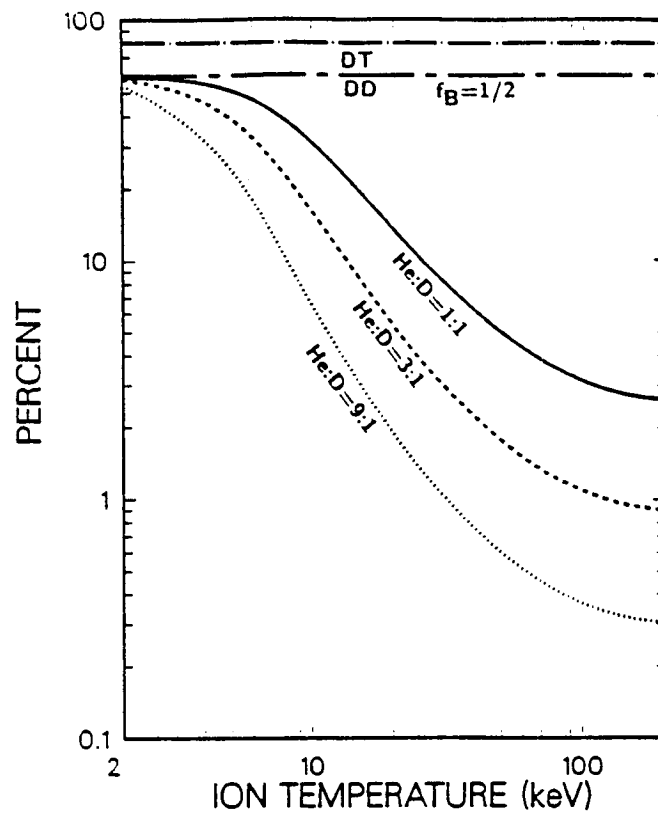


Figure 4. The percent of thermonuclear energy released in the form of neutrons by the DT, DD, and D-He3 fuel cycles. Note the variation of He3 to D ratio.

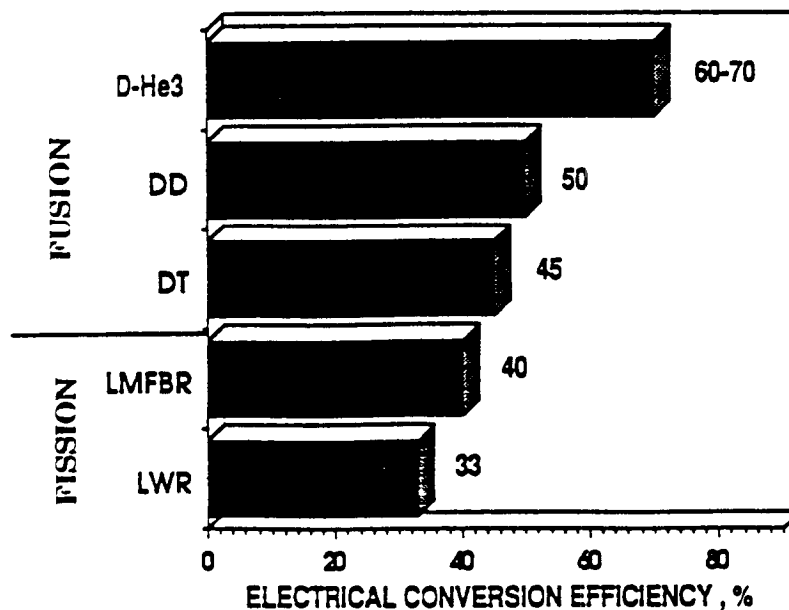


Figure 5. A comparison of overall conversion efficiencies of nuclear energy to electricity. The use of direct electrostatic or electromagnetic energy conversion schemes greatly enhances the performance of fusion devices.

#### IV-A. Efficiency

It is obvious that if only ~ 1% of the energy is released in neutrons, then the other ~ 99% is released as charged particles or photons. In linear magnetic fusion devices, where most of the energy leaks from the reactor in the form of highly energetic charged particles, one can convert their kinetic energy directly to electricity via electrostatic converters at  $\geq 80\%$ . This means that overall plant efficiencies of 60 to 70% are achievable. In toroidal magnetic devices, one can convert the synchrotron radiation emanating from the electrons (frequency ~ 3000 gigahertz) directly to electricity at roughly the same efficiencies (60-80%) through the use of rectenna. Depending on how the other forms of energy emitted from the plasma are utilized, the efficiency in toroidal devices may then be in the 40-60% range.

A comparison of the maximum conversion efficiencies that might be achieved by fission or fusion devices is shown in Figure 5. The important point to note is that fusion devices may increase the efficiency of fuel usage by a factor of 50 to 100% compared to fossil fuels or fission reactors. Such considerations are very important for thermal pollution in a terrestrial setting, but they are, in fact, critical to power plants that may operate in space. The rejection of heat in space is very, very costly.

#### IV-B. Radiation Damage

When high energy neutrons, such as the 14 MeV neutrons emitted from the DT reactions, run into structural reactor components, they can greatly reduce the mechanical performance of those components and induce significant long-lived radioactivity. With our present state of knowledge, it will be difficult to operate a fusion reactor for more than a few years before the metallic components become so brittle that they will have to be replaced. This requires shutting the reactor down, handling highly radioactive components, exposing workers to ionizing radiation, and generating large volumes of radioactive waste. Our best estimates at this time are that 2 to 3 reactor-years are about the limit for present day materials. Since reactors should operate for 30 or more years, such changeouts will occur 10 or more times during the lifetime of a typical DT fusion plant.

On the other hand, if we can reduce the neutron fraction to ~ 1% of the energy released in the D-He3 cycle, then the metallic components will last ~ 80 times longer than in a DT reactor. Such an extension is enough to completely obviate the necessity for component change due to neutron damage. This longer life will have profound economic and environmental benefits in a society based on the use of fusion energy.

#### IV-C. Reduced Radioactivity

Because of the much smaller number of neutrons, the induced radioactivity in the reactor walls will also be reduced by a factor of ~ 80. In today's DT fusion reactor designs, special materials have to be developed to avoid generating large amounts of high level wastes that must be placed in deep underground repositories. Conventional steels for example, would become so radioactive that 10's of tonnes per reactor-year could only be disposed of in one of the national deep repositories scheduled for operation near the turn of the century. On the other hand, these same materials would last the full 30 year

life of a D-He3 plant and still could be disposed of as low level class C waste buried in near surface disposal sites. If low activation steels are developed, then such alloys, after 30 years of operation could be buried along with medical waste in near-surface sites. Aside from the tremendous savings in cost, one would find that these D-He3 wastes would decay to benign levels in less than 100 years instead of the 1000's of years required for current fission and fusion devices.

#### IV-D. Safety

One of the most severe accidents that could occur in a DT fusion plant is the complete loss of coolant along with a complete breach of reactor containment. The afterheat in a DT reactor can be sufficient to release large amounts of tritium and radioisotopes from the reactor structure. At present, it is not known whether we can keep critical components from melting in a commercial DT reactor.

In a D-He3 reactor, two fundamental characteristics prevent such dire consequences. First, the afterheat (which comes directly from the neutron activation products) is so low that in the event of the most severe accident to be imagined, and if no heat leaked from the system (e.g., if the entire reactor was wrapped in a perfect thermally insulating blanket), the maximum temperature increase in a week would be ~ 500°C (still 1000°C below its melting point). Secondly, the tritium inventory in a D-He3 plant can be as little as 2 grams. The complete release of this tritium in a rain storm could still cause no more exposure to a member of the public living next to the D-He3 reactor than he or she normally receives from cosmic rays or radon gas in a year's time. *In other words, there is no possibility of an offsite fatality due to the release of all the volatile tritium radioactivity in a D-He3 fusion power plant and the consequences of such a release would be hard to detect among the populace.*

#### IV-E. Cost of Electricity

There are features of the D-He3 fuel cycle which strongly suggest that it will provide electricity more cheaply than a DT fusion power plant. These are

- a) lower capital cost
- b) lower operation and maintenance costs
- c) higher efficiency
- d) higher availability.

The first point is based on a comparison of two recent D-He3 reactor designs, Ra [3] and Apollo [4] to 17 previous DT reactor designs, most done by the same group with the same costing philosophies. The results of this comparison are shown in Figure 6. The direct capital cost of the Apollo-L D-He3 system is ~ 20-50% lower than comparable DT plants. The reason for this has to do with the greatly reduced balance of plant costs (i.e., that part of the power plant outside the fusion reactor) associated with conventional steam generators and turbines. It also has to do with the fact that D-He3 plants, which contain such low levels of  $T_2$  and radioactivity, can use conventional construction grade material, thus avoiding the high nuclear-grade material costs associated with fission and probably with DT fusion reactors.



Because of the low radioactivity and because there should be no repair required from neutron damage, the number of plant personnel can be greatly reduced compared to a DT plant. The use of solid state electrical conversion equipment also will require less maintenance personnel.

The higher electrical efficiency will have a direct effect on the specific cost parameters. For example, the capital cost per kWe will be lower for the same thermal power, and the cost of heat rejection equipment (i.e., cooling towers) will be greatly reduced.

Finally, the ultimate cost of electricity, in mills per kWh, can be reduced if the plant stays on line for a larger fraction of its total lifetime. As stated previously, a DT power plant has to be shut down frequently to change neutron-damaged components. The duration of the down time will be adversely affected by the induced radioactivity and the problems associated with tritium contamination. It is also well known that plants which use a high-pressure steam cycle require, on average, on the order of 10-15% of their total life time to repair steam turbines and heat exchangers. The use of solid state conversion equipment should reduce that number similar to the way solid state TV sets are more reliable than those which used vacuum tubes.

#### IV-F. Shorter Time to Commercialization

The time from now to commercialization of D-He3 fusion could be shorter than the time to commercialize the DT cycle even if it takes longer to solve the remaining physics problems. The reason for this again lies in the low fraction of neutrons released in the D-He3 cycle and the need to develop a whole new class of metals and alloys to withstand the damage associated with the 14 MeV neutrons from the DT cycle. Conservative estimates of the cost to solve this problem include a materials test facility (1-2 B\$ capital plus 10-15 years operating time requiring another 1-2 B\$ in operating expenses), and a completely new blanket test facility in a demonstration power plant (3-4 B\$ + 10-15 years and ~ 5 B\$ operating costs) before one could get to a commercial system. Add to this significant sum the cost of an auxiliary technology program for 20-30 years beyond the solution of the physics problems (another 10-20 B\$) and we can see that an additional ~ 30 B\$ and 30 years could be required to commercialize DT fusion after the successful DT physics operation in the ITER class of fusion devices in the year 2005.

On the other hand, if the ITER could be slightly modified (for less than 10% of its present cost) to ignite D-He3, then the same reactor could also be used to generate electricity in a demonstration reactor mode by 2005-2010. Since there is no need for a materials test facility nor for the need of developing breeding blankets, a new D-He3 commercial plant could be operational by the year 2015-2020, a full 15-20 years sooner than possible with the DT cycle.

#### V. Availability of Helium-3

##### V-A. Terrestrial Resources

It was commonly believed in the fusion community that after the questions of plasma physics have been solved, the next single largest barrier to the widespread study of the D-He3 reaction would be the lack of any large identified terrestrial source of helium-3. Studies by the SOAR (Space Orbiting

## HISTORICAL CAPITAL COSTS OF COMMERCIAL FUSION REACTOR DESIGNS

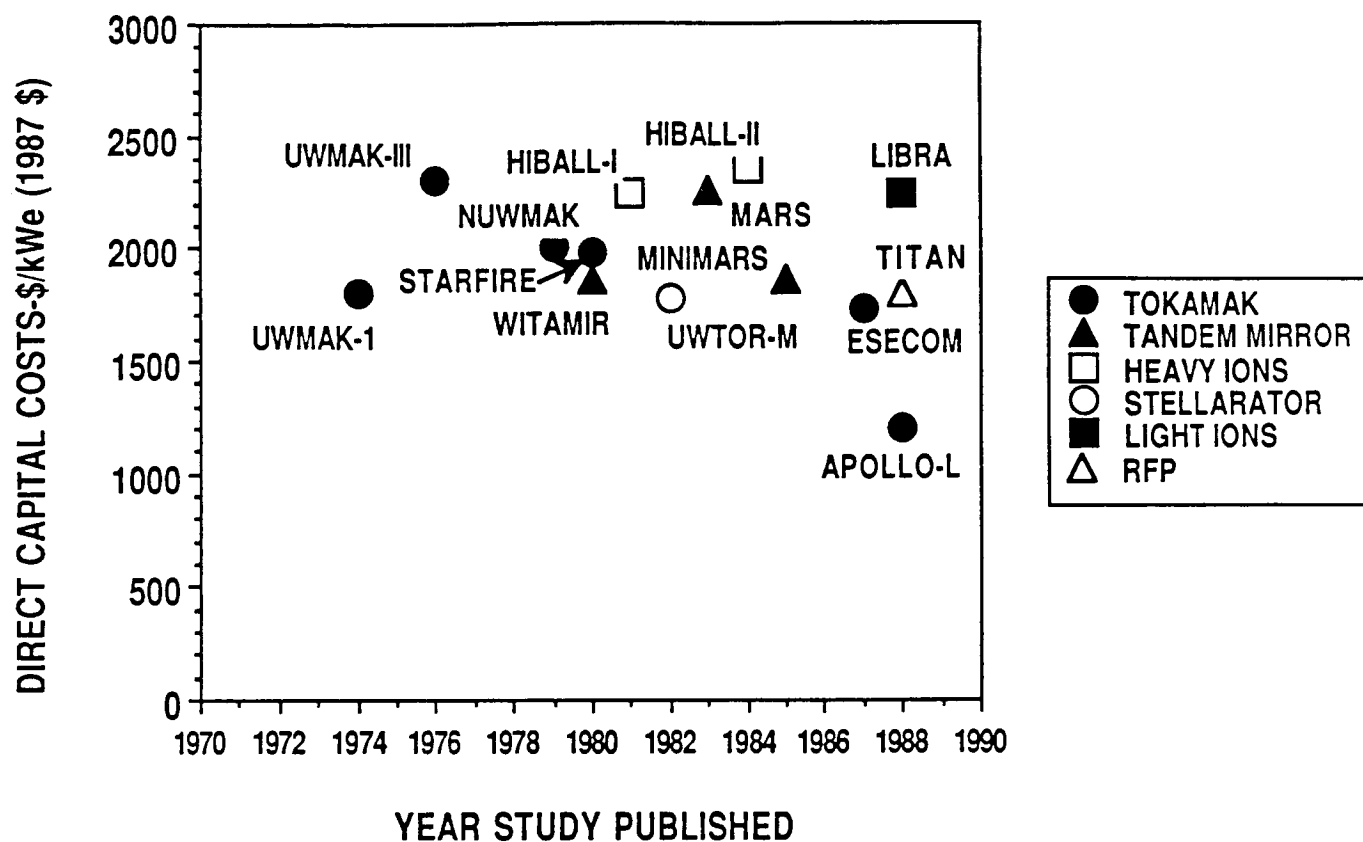


Figure 6. Historical Capital Costs of Commercial Fusion Reactor Designs

# RESERVES OF He3 THAT COULD BE AVAILABLE IN THE YEAR 2000

SOURCE	CUMULATIVE AMOUNT (kg)	PRODUCTION RATE AFTER YEAR 2000 (kg/y)
<u>PRIMORDIAL-EARTH</u>		
● US HELIUM STORAGE	29	-----
● US NATURAL GAS RESERVES	187	-----
<u>TRITIUM DECAY</u>		
● US NUCLEAR WEAPONS	300	~15
● CANDU REACTORS	10	~2
<u>TOTAL</u>	>500	~17

Note: 1 kg of He3 burned with 0.67 kg of deuterium yields 19 MW-y of energy

Table 1. Amounts of He3 That Could Be Available in the Year 2000

Advanced Reactor) concept at the University of Wisconsin in 1985 identified only small amounts of indigenous He3 on the Earth and a roughly equal-sized source from the decay of tritium ( $t_{1/2} = 12.3$  years) in the U.S. thermonuclear weapons program (see Table 1).

Most of the primordial He3, present at the formation of the Earth, has long since diffused out of the Earth and been lost in outer space. What is left in any retrievable form is contained in the underground natural gas reserves. Table 1 reveals that the total He3 content in the strategic He reserves stored underground amounts to only some 30 kg. If one were to process the entire United States known conventional natural gas reserves, another 200 kg of He3 might be obtained.

Another source of He3 on Earth is from the decay of tritium ( $t_{1/2} = 12.3$  years). When  $T_2$  decays, it produces a He3 atom and a beta particle. Simple calculations of the inventory of  $T_2$  in U.S. thermonuclear weapons shows that if all the He3 were collected, some 300 kg would be available by the year 2000. Presumably about the same amount of He3 would be available from the weapons stockpile of the USSR. The equilibrium production of He3 (assuming no future change in weapons stockpiles) is around 15 kg per year in each country. It may seem strange to rely on a by-product from weapons for a civilian application, but the He3 commercially available today is from just such a process. One can purchase up to 1.38 kg of He3 per year directly from the U.S. government (10,000 liters at STP) all of which comes from  $T_2$  decay. Obviously, considerably more is available, and simple calculations of the tritium production from U.S. facilities at Savannah River indicate that tritium production could be in the 10-20 kg per year range. This would imply an "equilibrium" He3 production rate of ~ 10-20 kg/year minus losses in processing.

One could also get smaller amounts of He3 from the  $T_2$  produced in the heavy water coolants of Canadian CANDU reactors. This could amount to 10 kg of He3 by the year 2000, and He3 will continue to be generated in these plants at a rate of ~ 2 kg per year thereafter.

It should be noted again that 1 kg of He3, when burned with 0.67 kg of D, produces approximately 19 MW-y of energy. This means that by the turn of the century, when there could be several hundred kg's of He3 at our disposal, the potential exists for several thousand MW-y of power production. The equilibrium generation rate from  $T_2$  resources alone could fuel a 300 MWe plant indefinitely if it were run 50% of the time.

Clearly, there is enough He3 to build an Experimental Test Reactor (ETR) (a few hundred MW's running 10-20% of a year) and a demonstration power plant of hundreds of MWe run for many years. This could be done without ever having to leave the earth for fuel. The real problem would come when the first large (GWe) commercial plants could be built around the year 2015.

#### V-B. What and Where are the He3 Resources on the Moon?

Wittenberg et al. [5] showed in September 1986 how the He3, first discovered on the Moon by the Apollo-11 mission, could be utilized in a fusion economy. Since that time, work at the University of Wisconsin has elaborated on the original idea. A few highlights will be summarized here.

The origin of lunar He3 is from the solar wind (i.e., the charged particles leaking from the sun and "blowing" on the rest of the bodies in the solar system). Using data which showed that the solar wind contains ~ 4% helium atoms and that the He3/He4 ratio is ~ 480 appm, it was calculated that the surface of the Moon was bombarded with over 250 million metric tonnes in 4 billion years. Furthermore, because the energy of the solar wind is low (~ 3 keV for the He3 ions), the ions did not penetrate very far (< 0.1 micron) into the surface of the regolith particles (lunar soil). The fact that the surface of the Moon is periodically stirred, as the result of frequent meteorite impacts, results in the helium being trapped in soil particles to depths of several meters.

Analysis of Apollo and Luna regolith samples revealed that the total helium content in the Moon minerals ranges from a few to 70 wtpm (see Figure 7). The higher concentrations are associated with the regolith on the old titanium-rich basaltic Maria of the Moon, and the lower contents are associated with the Highland rocks and Basin Ejecta. Clearly the higher concentrations are in the most accessible and minable material. Using the data available, it is calculated that roughly a million metric tonnes of He3 are still trapped in the surface of the Moon [5] (see Table 2).

The next step is to determine the most favorable location for extracting this fuel. Cameron [6] has shown that there is an apparent association between the helium and TiO<sub>2</sub> content in the samples. Assuming that this is generally true, he then examined the data on spectral reflectance and spectroscopy of the Moon which showed that the Sea of Tranquility (confirmed by Apollo 11 samples) and certain parts of the Oceanus Procellarum were particularly rich in TiO<sub>2</sub>. It was then determined, on the basis of the large area (190,000 km<sup>2</sup>) and past U.S. experience, that the Sea of Tranquility would be the prime target for initial investigations of lunar mining sites. This one area alone appears to contain more than 8,000 tonnes of He3 to a depth of 2 meters. Backup targets are the TiO<sub>2</sub>-rich basalt regolith in the vicinity of Mare Serenitatis sampled during Apollo 17 and areas of high-Ti regolith, indicated by remote sensing, in Mare Imbrium and other mare of the lunar western hemisphere [6].

#### V-C. How Would the He3 be Extracted?

Since the solar wind gases are weakly bound in the lunar regolith it should be relatively easy to extract them. Pepin [7] found (Figure 8) that heating lunar regolith caused the He3 to be evolved above 200° C and by 600° C, approximately 75% of the He gas could be removed.

There are several methods by which the He could be extracted and a schematic of one approach is shown in Figure 9. In this unit, the loose regolith, to a depth of 60 cm, is scooped into the front of the robotic unit. It is then sized to particles less than 100 microns in diameter (about 65% of the regolith) because there seems to be a higher concentration of solar gases in the smaller particles (presumably because of the high surface to volume ratio). After beneficiation, the concentrate is preheated by heat pipes [4] and then fed into a solar-heated reaction chamber. At this point, it is anticipated that heating to only 600 or 700°C is required, and the volatiles (H<sub>2</sub>, He4, He3, H<sub>2</sub>O, C compounds, N<sub>2</sub>) are collected. The spent regolith concentrate is discharged through recuperative heat exchangers to recover 90%

### HELIUM-3 CONTENT OF LUNAR REGOLITHS

LOCATION	% LUNAR SURFACE	AVE. HELIUM CONC. wtppm	TONNES He3
MARIA	20	30	600,000
HIGHLANDS & BASIN EJECTA	80	7	500,000
TOTAL			1,100,000

Table 2. Helium-3 Content of Lunar Regoliths

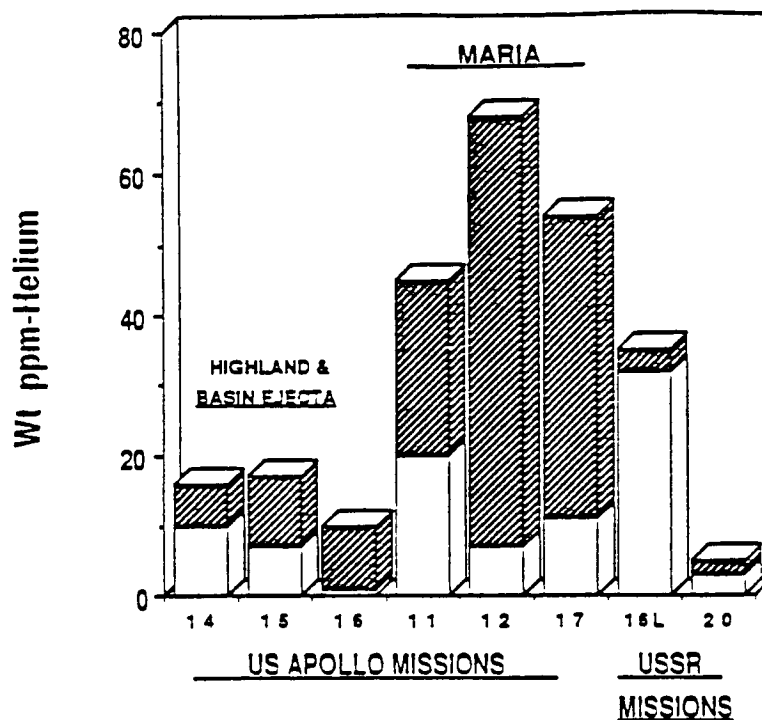


Figure 7. Range of helium concentration measured in U.S. Apollo and USSR Luna samples. Cross-hatched region gives range.

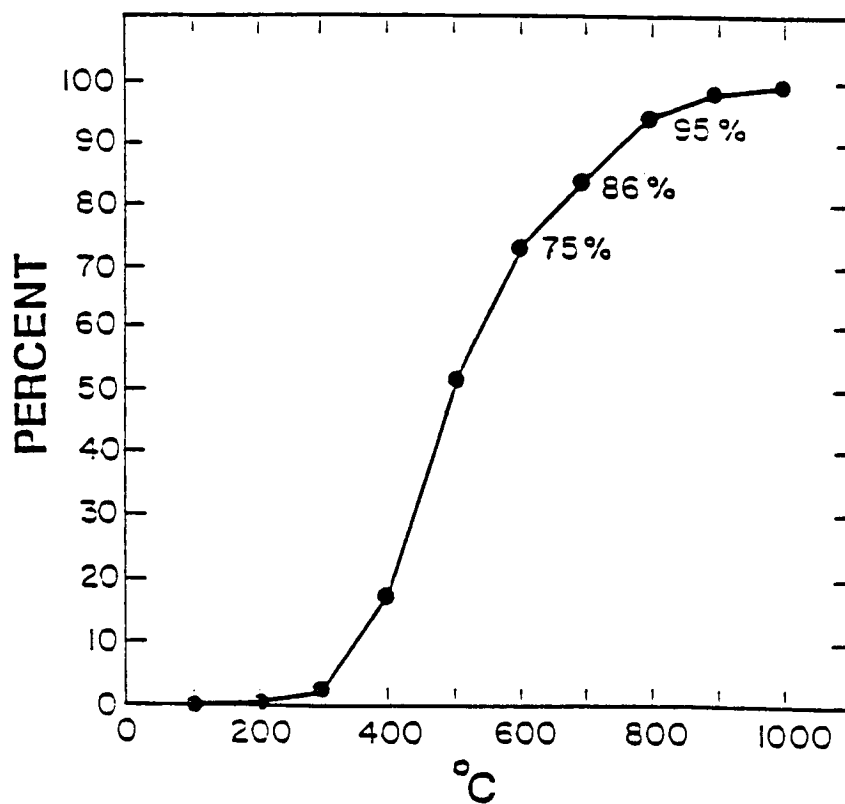


Figure 8. Evolution of He3 from lunar regolith as measured by Pepin [3] in 1970.

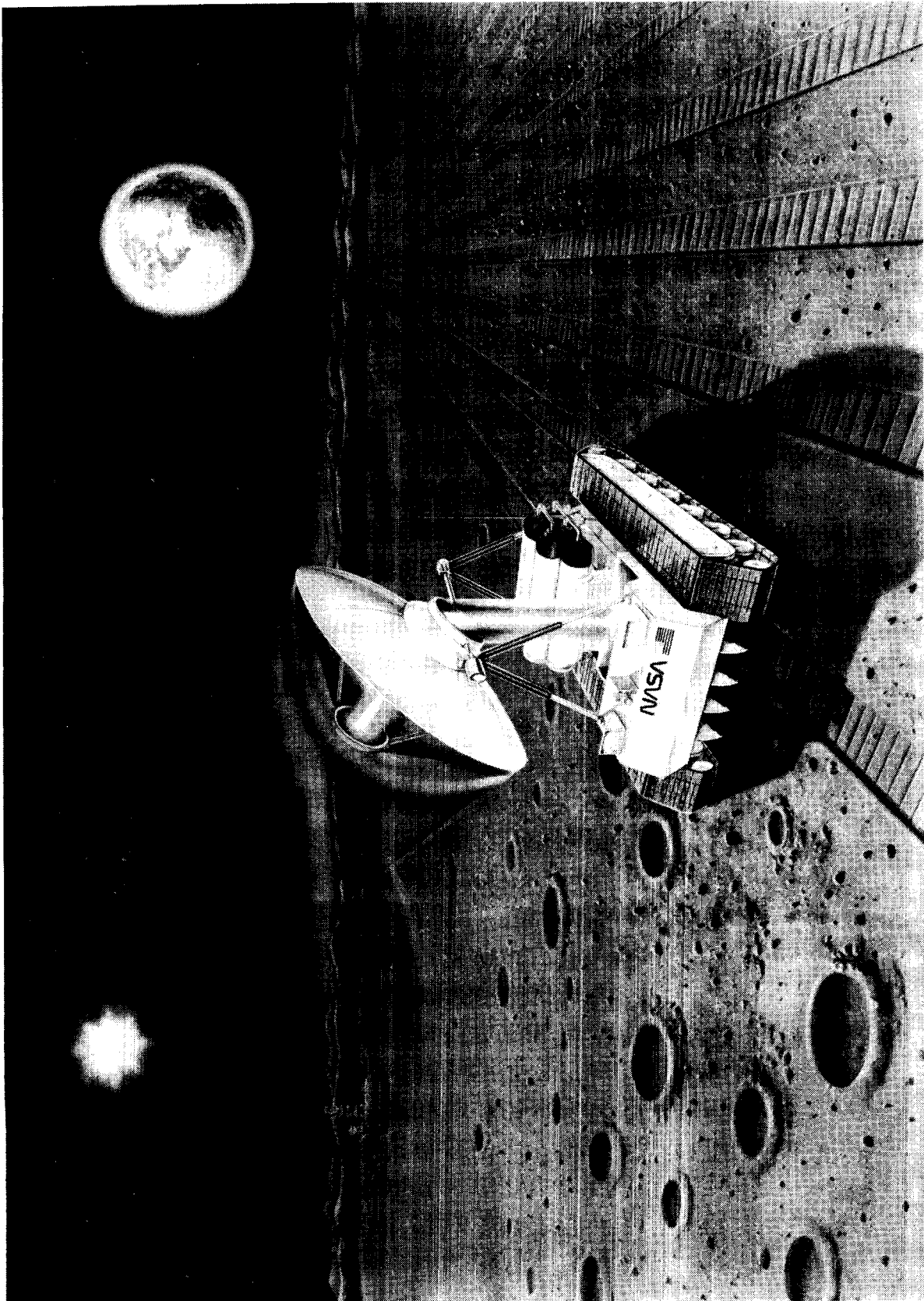


Figure 9. Design of lunar vehicle to extract He3 from regolith using direct solar radiation.



of its heat. The spent regolith is finally dropped off the back of the moving miner. Note that in the 1/6 gravity environment, relatively little energy is expended lifting material.

Of course, this solar energy-driven scheme would only work during the lunar day, but orbiting mirrors, nuclear reactor heat from a mobile power plant, or indirect radiofrequency (RF) heating from electricity generated at a central power plant on the Moon could extend the operating time. Alternative schemes are being examined through parametric analyses of such variables as particle size vs. temperature vs. yield, mining depth vs. He3 concentration vs. particle size distribution, manned operation vs. robotic operations vs. maintenance costs, mechanical particle separation vs. gaseous particle separation vs. yield, solar vs. nuclear power, etc.

Once the lunar volatiles are extracted, they can be separated from the helium by isolation from the lunar surface and exposure to outer space ( $< 5$  K) during the lunar night. Everything except the helium will condense and the He3 can be later separated from the He4 by superleak techniques well established in industry [5].

For every metric tonne (1000 kg  $\approx$  2200 pounds) of He3 produced, some 3100 tonnes of He4, 500 tonnes of nitrogen, over 4000 tonnes of CO and CO<sub>2</sub>, 3300 tonnes of water, and 6100 tonnes of H<sub>2</sub> are produced (see Figure 10). The H<sub>2</sub> will be extremely beneficial on the Moon for lunar inhabitants and for propellants. Transportation of that much H<sub>2</sub> to the Moon, even at 1000 \$/per kg (about 1/10 of present launch costs), would cost ~ 6 billion dollars. As noted below, the He3 itself could be worth as much as ~ 2 billion dollars per tonne. Of the other volatiles, the N<sub>2</sub> could also be used for plant growth, the carbon also for plant growth, for manufacturing or atmosphere control, and the He4 for pressurization and as a power plant working fluid. Oxygen, either from the water or carbon compounds, could be used for interior atmospheres or for fuel in rockets from the Moon.

The environmental impact to the Moon as a result of this type of volatile extraction would be minimal. For example, there would be "tracks" on the Moon and the surface would be smoothed and slightly "fluffed up" as the spent regolith is redeposited. The vacuum at the lunar surface might also be temporarily affected but, due to the low gravity level, most of the gas atoms will leave the surface of the Moon during the lunar day.

#### V-D. How Much is the He3 Worth?

While it is hard to anticipate the cost of energy in the future, one can anticipate what we might be willing to pay for fuel based on today's experience. First of all, it is worthwhile to get a feeling for how much energy is contained in the He3 on the Moon. If the ultimate resource base is 1 million metric tonnes, then there is some 20,000 TW-y of potential thermal energy on the Moon. This is over 10 times more energy than that contained in economically recoverable fossil fuels on earth. This amount of energy is also 100 times the energy available from economically recoverable U on earth burned in Light Water Reactors on a once through fuel cycle or roughly twice the energy available from U used in Fast Breeder Reactors.

## BY-PRODUCTS OF LUNAR HELIUM-3 MINING

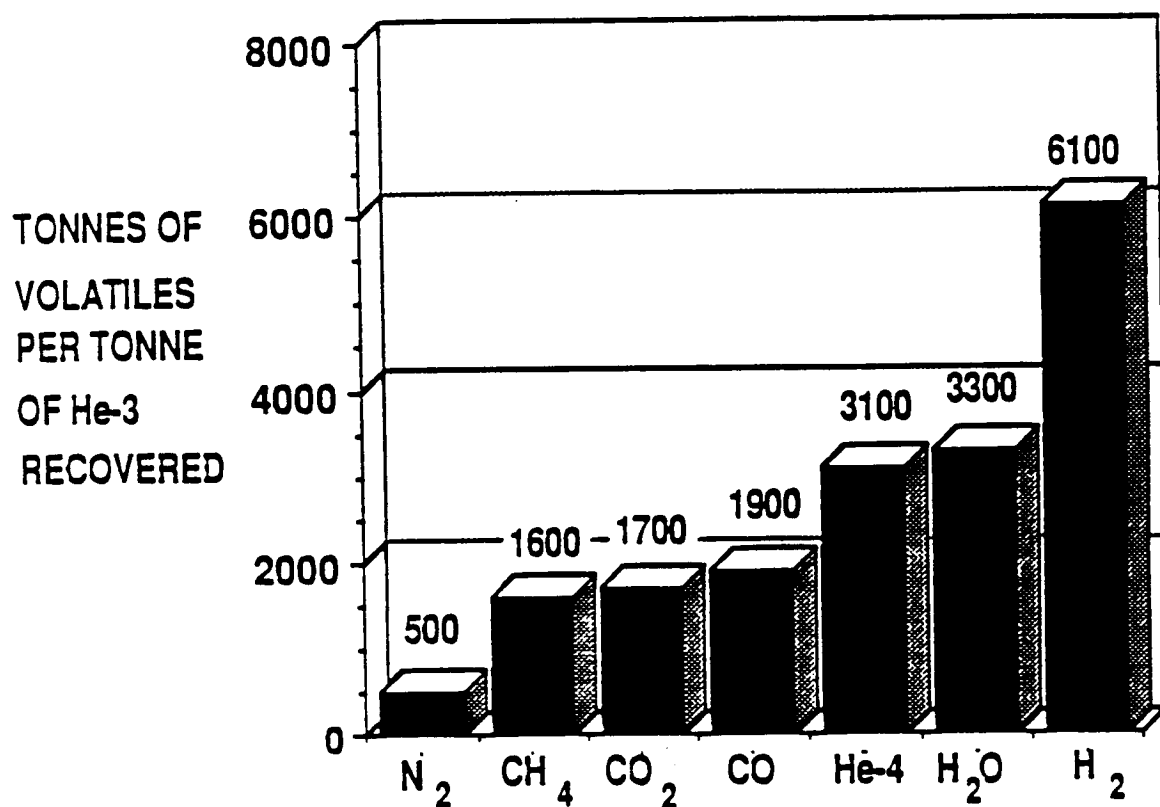


Figure 10. By-Products of Lunar Helium-3 Mining

The second point is that only 25 tonnes of He3, burned with D<sub>2</sub> in a Ra [3] type reactor, would have provided the entire U.S. electrical consumption in 1987 (some 285,000 MWe-y). The 25 tonnes of condensed He3 could fit in the cargo bay of a spacecraft roughly the size of the U.S. shuttle.

A third point is that in 1987, the U.S. spent over 40 billion dollars for fuel (coal, oil, gas, uranium) to generate electricity. This does not include plant or distribution costs, just the expenditure for fuel. If the 25 tonnes of He3 just replaced that fuel cost (while the plant and distribution costs stayed the same) then the He3 would be worth approximately 1.6 billion dollars per tonne. At that rate, it is the only thing we know of on the Moon which appears to be economically worth bringing back to earth.

An obvious question at this point is how much does it cost to obtain He3 from the Moon? The answer to that depends on three things:

- (1) Will the U.S. develop a Moon base for scientific or other mining operations without the incentive of obtaining He3?
- (2) If the answer to the above question is yes, then how much will the incremental costs of mining He3 be after manned lunar bases are already in place?
- (3) How will the benefits of the side products be treated? For example, will one be able to "charge" the lunar settlement for the H<sub>2</sub>, H<sub>2</sub>O, N<sub>2</sub>, He, or carbon compounds extracted from the lunar regolith?
- (4) Will the ultimate export of volatiles to a Mars settlement add a significant rate of return to the enterprise?

The answer to question 1) may be yes. In a 1987 report to NASA, by the Ride Commission [10], it was stated that one of the 4 major future programs in NASA should be a return to the Moon and the establishment of a manned base early in the 21st century. This recommendation was made without any reference to the He3 mining possibilities. Furthermore, President Bush, called for a return to the moon on July 20, 1989 during the celebration of the 20th anniversary of the Apollo 11 landing on the moon. At this time, it appears reasonable to assume that the cost of returning to the Moon will be borne by the U.S. government or by an international entity as a general investment in science.

The answer to question 2) cannot be given at this time but should be the subject of study in the near future. It appears that, based on the mobile mining concept described earlier, that the equipment required to produce 25 tonnes per year could be transported to the Moon for well under 30 billion dollars (e.g., at 1000 \$/kg this would allow 30,000 tonnes to be transported to the Moon). Operational costs should be well under a billion dollars per year even if no use of lunar materials is allowed. The above costs are to be compared to 500-1000 B\$ in revenue from the He3 mining during the useful life of the equipment.

The possibilities of "selling" the by-products of the He3 to lunar colonies is also very intriguing. The by-products from mining just one tonne of He3 would support the annual lunar needs (properly accounting for losses through leakage and through waste recycling) of [11]:

1,400 people for N<sub>2</sub> (food and atmosphere)  
22,000 people for CO<sub>2</sub> used to grow food  
45,000 people for H<sub>2</sub>O.

If the cost of transporting the equipment to extract these volatiles from the lunar regolith is written off against the savings in sending up life support elements such as  $H_2$ ,  $N_2$ , or carbon for manned lunar bases, then it is possible that the cost of He3 may in fact be negligible. If that were true then the cost of electricity from D-He3 fusion power plants would indeed be much cheaper than from DT systems and possibly even from fission reactors (without taking credit for all the environmental advantages of the D-He3 fuel cycle).

To answer the question posed by the title of this section, it appears that a realistic figure for the worth of He3 on the earth is ~ 1 or 2 billion dollars per tonne (1000 \$/g). This should allow D-He3 fusion plants to be competitive with DT systems and provide adequate incentive for commercial retrieval from the Moon. This latter point is currently the subject of the Enterprise study conducted by NASA.

#### V-E. What is the Current Attitude Toward He3 Development?

The current domestic and international policy environment may require significant modification to enhance the development of helium-3 fusion power on earth or helium-3 mining on the Moon. Policy issues that may affect the ultimate availability of helium-3 fusion power include the following:

1. U.S. Commitment: There is no firm commitment by the U.S. Department of Energy to the development of commercial helium-3 fusion power or by NASA to the creation of a space and lunar infrastructure that would support such a commitment. However, the two agencies now meet on a regular basis to coordinate research into D-He3 fusion and it is possible that such efforts could provide the basis for a coordinated program.
2. Soviet Commitment: There have been strong indications that, beyond a research interest in helium-3 fusion, the Soviets have focused their deep space related development on Mars rather than on lunar resources. However, recent public statements by Soviet space and fusion researchers at the Kurchatov Institute in Moscow suggest that D-He3 fusion and lunar He3 are of increasing interest to them.
3. U.S.-Soviet Cooperation: The lack of long range U.S. goals related to helium-3 fusion and the apparent focus of long range Soviet goals on Mars suggest that near term cooperation related to helium-3 mining on the Moon is unlikely unless a specific new stimulus is provided.
4. European Potential: 1992 will see a major step toward a United States of Europe with the technical and economical potential to be a major player in helium-3 fusion and lunar resource development. Indeed, Europe will have the potential to "go it alone" even though it may or may not decide to use that capability. It is not clear that the rest of the world has fully recognized this looming change in Europe's status as a "Great Power." In any case, preliminary investigations of the use of He3 in NET, the Next European Torus, have been conducted and experiments in the European JET device have released 100 kW of thermonuclear power from the D-He3 reactor, a world record!

5. Asian Potential: Several Pacific rim nations, in aggregate, also have the technical and economic potential to be a major player in helium-3 fusion and lunar resource development. This potential will be enhanced if China becomes associated with these nations. The difficulties of Asian cooperation, however, appear to significantly exceed those of Europe.
6. Third World Desires: The Third World nations (i.e., Group of 77) can be anticipated to push for inclusion in the distribution of economic benefits from any helium-3 enterprise and possibly in the actual management of a lunar mining enterprise.
7. International Cooperation: Existing international arrangements (e.g., the Moon Treaty and INTELSAT) may provide the basis for future cooperation in helium-3 fusion development and lunar helium-3 production. In this context, the ITER agreement between the United States, the USSR, Japan, and the European Community, with China and Canada in associate status, may provide the basis for initiating such cooperation.
8. Environmental Protection: A qualitative net assessment of the environmental benefits of helium-3 fusion appears to be strongly in favor of its development when the full environmental impact of fossil and fission fuels is considered. However, the general emotional resistance to the development of nuclear power in the U.S. may prolong decision making related to helium-3 fusion.

#### References for Appendix B-6

- [1] T.J. Dolan, "Fusion Research," Pergamon Press, New York, 1982.
- [2] W.M. Stacey, Jr., "Fusion Plasma Analysis," Wiley, New York, 1981.
- [3] G.L. Kulcinski, G.A. Emmert, H. Attaya, J.F. Santarius, M.E. Sawan, I.N. Sviatoslavsky, and L.J. Wittenberg, "Commercial Potential of D-He3 Fusion Reactors," Proc. 12th Symp. Fusion Engr., Monterey, CA, IEEE-87CH2507-2, p. 772 (1987).
- [4] G.L. Kulcinski, et al., "Apollo - An Advanced Fuel Fusion Power Reactor for the 21st Century," Fusion Technology, 15, 1233 (1989).
- [5] L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, Fusion Technology, 10, 167 (1986).
- [6] E.N. Cameron, Univ. of Wisc. Report, WCSAR-TR-AR3-8708 (1987) also to be published in Proc. 2nd Lunar Base Conf., Houston, TX (1988).
- [7] R.O. Pepin et al., Proc. 11th Lunar Scientific Conf., Vol. 2, 1435 (1970).
- [8] I.N. Sviatoslavsky and M. Jacobs, "Mobile Helium-3 Mining and Extraction System," to be published in Proc. 2nd Lunar Base Conf., Houston, TX (1988).
- [9] G.L. Kulcinski, E.N. Cameron, J.F. Santarius, I.N. Sviatoslavsky, L.J. Wittenberg, and H.H. Schmitt, "Fusion Energy from the Moon for the 21st Century," to be published in Proc. 2nd Lunar Base Conf., Houston, TX (1988).
- [10] "Leadership and America's Future in Space," A Report to the Administrator by Dr. S.K. Ride, NASA, August 1987.
- [11] R.J. Bula, L.J. Wittenberg, T.W. Tibbitts, and G.L. Kulcinski, "Potential of Derived Volatiles for Life Support," to be published in Proc. 2nd Lunar Base Conf., Houston, TX (1988).